BESIII和PANDA上的电磁量能器软件

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2023年粒子物理实验计算软件与技术研讨会
6月10日，山东大学

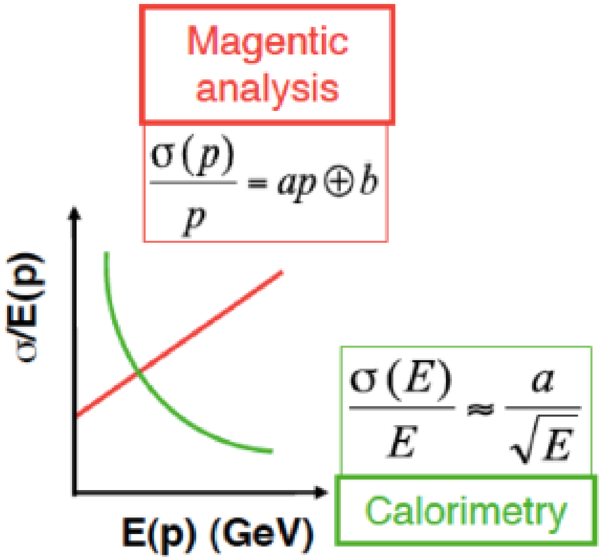
报告提纲

- 量能器简介
- BESIII和PANDA的量能器软件：模拟、重建和刻度
- 总结

为什么需要量能器?

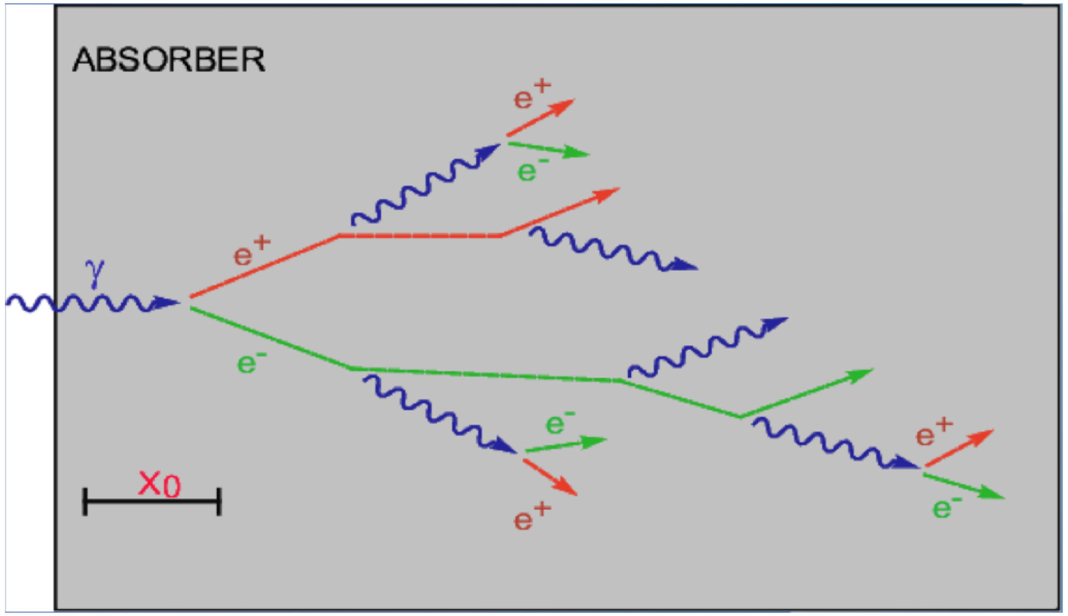
- **量能器是理想的测量高动量粒子的探测器**
  - 分辨随能量的增大而减小：$\frac{\sigma_E}{E} \propto \frac{1}{\sqrt{E}}$
  - （径迹探测器：$\frac{\sigma_p}{p} \propto \frac{p}{L^2}$）

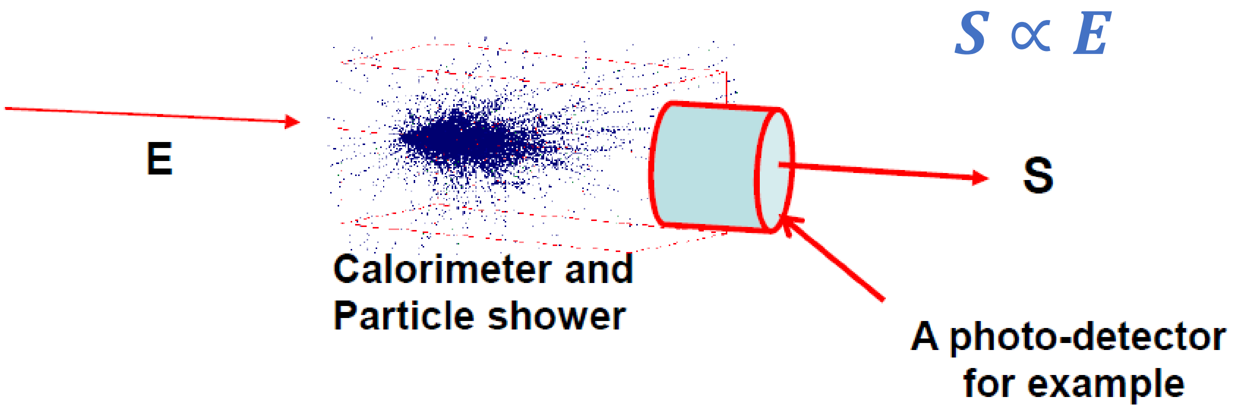
- **其它的优势：**
  - 簇射的深度$\propto \ln(E)$：尺寸可控
  - 可以覆盖全立体角：高探测效率
  - 信号成形快：可用于触发
  - …



电磁量能器探测原理

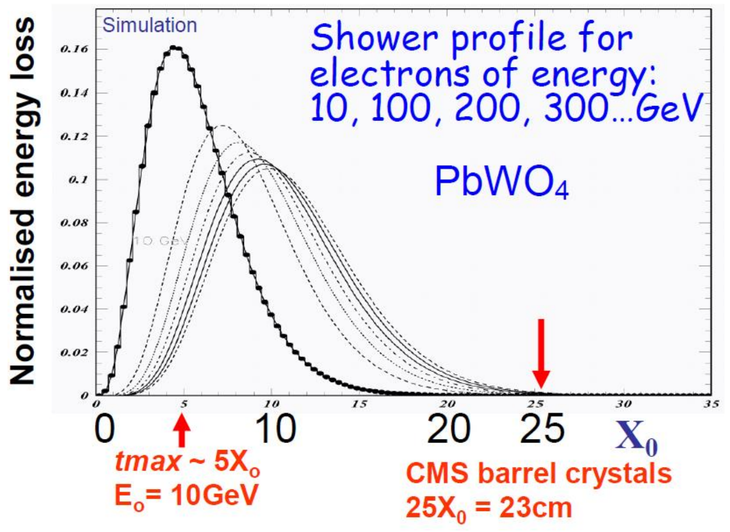
- 入射粒子 (能量 E) 与量能器物质发生相互作用，产生电磁簇射
  - 主要是电子的韧致辐射和光子的对产生的级联过程
- 电磁簇射在量能器中发展完全，中间产生的次级粒子的能量沉积在量能器中，通过后端的光子探测器收集信号 $S(\propto E)$
- 通过对电磁簇射的测量，从而测量光子和电子的能量和位置信息及穿过量能器的其它带电粒子的沉积能量



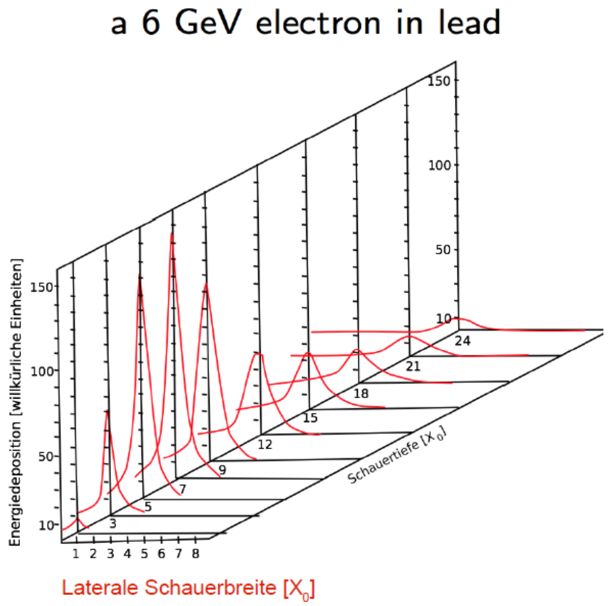


电磁簇射的特征

- **纵向发展分布**
  - $t_{max} \propto \ln(E_0/E_c)$
  - $L(95\%) = t_{max} + 0.08Z + 9.6X_0$



- **横向发展分布**
  - 主要由簇射中电子的库仑散射决定
  - Moliere半径：$R_M \approx \frac{21MeV}{E_c} X_0$
  - $R(95\%) = 2R_M$



全吸收型电磁量能器晶体的性质

晶体性质决定了电磁簇射的特征

表 7－1 常用无机闪烁晶体的性能

晶 体	NaI(Tl)	CsI(Tl)	BGO	$PbWO_4$
比重(g/m^3)	3.67	4.51	7.13	8.28
辐射长度(cm)	2.59	1.86	1.12	0.89
莫里哀半径(cm)	4.8	3.8	2.3	2.0
dE/dx(Mev/cm)	4.8	5.6	9.2	13.0
核作用长度(cm)	41.4	37	21.8	18
折射系数(480 nm)	1.85	1.79	2.15	2.16
发射峰波长(nm)	410	560	480	420～560
相对光输出	100	45(PMT) 140(PD)	15	0.6 at RT 2.5 at -25°C (PWO-II)
发光温度系数(%/℃)	≈0	0.3	－1.6	－1.9
发光衰减时间(ns)	230	1000	300	10～50
潮解性	强	微	无	无
参考价格($/$cm^3$)	2	2	7	2.5

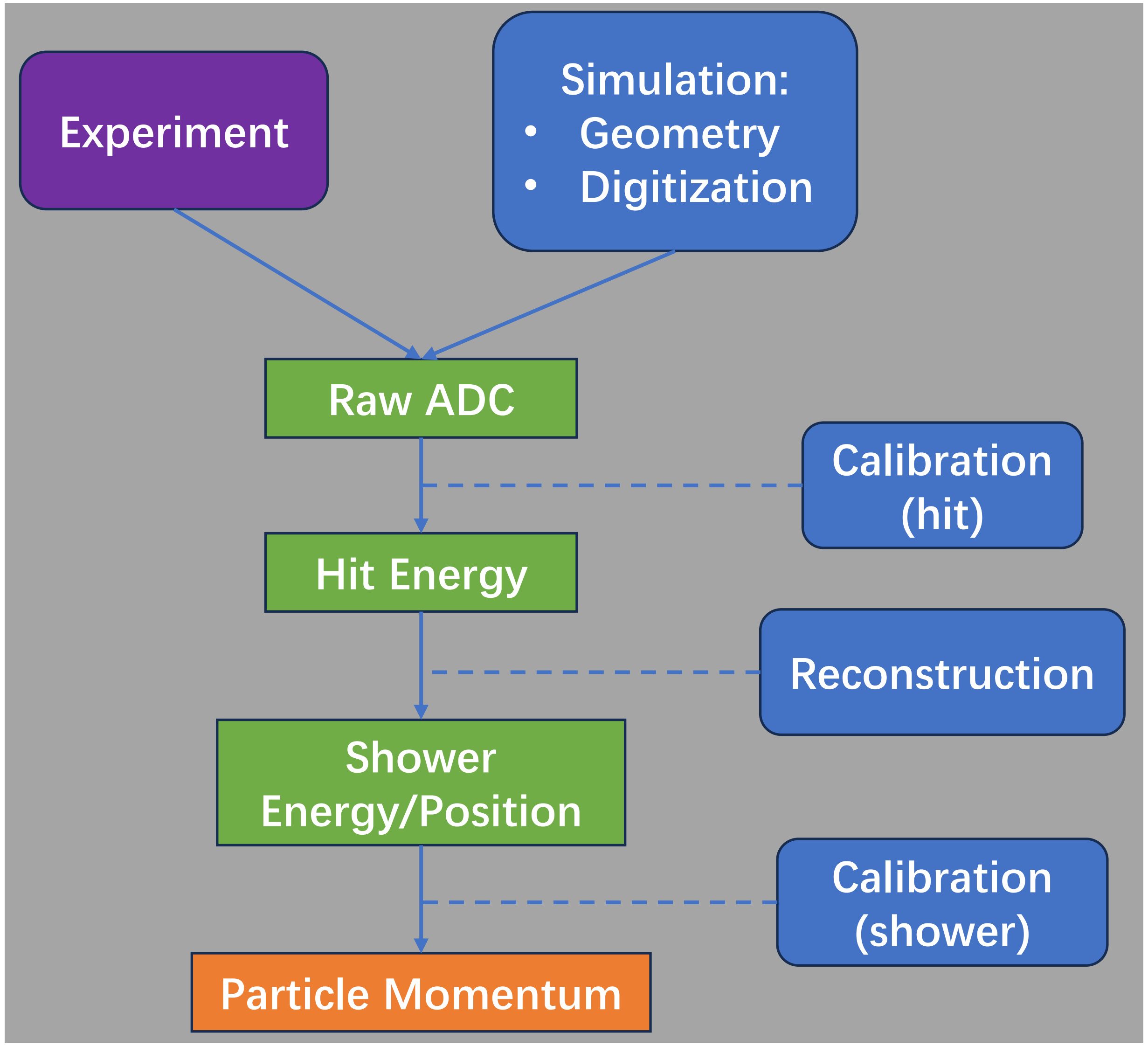
- **BESIII: CsI (Tl)**
  - 更高的光产额
- **PANDA: PWO-II**
  - 更紧凑的簇射
  - 更快的信号 (桶部最高事例率100 kHz)

能量分辨

- 簇射本征统计涨落：$\propto \frac{1}{\sqrt{E}}$
- 光子/电子在光子探测器中的统计涨落：$\propto \frac{1}{\sqrt{E}}$
- 电子学噪声：$\propto \frac{1}{E}$
- 能量泄露、刻度：$\approx constant$

- 总体能量分辨：
  - $\frac{\sigma_E}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c$

电磁量能器软件



实现量能器的性能要求，离不开高质量的离线软件

模拟/数字化：
- 与真实实验尽可能一致的几何和探测器/电子学响应

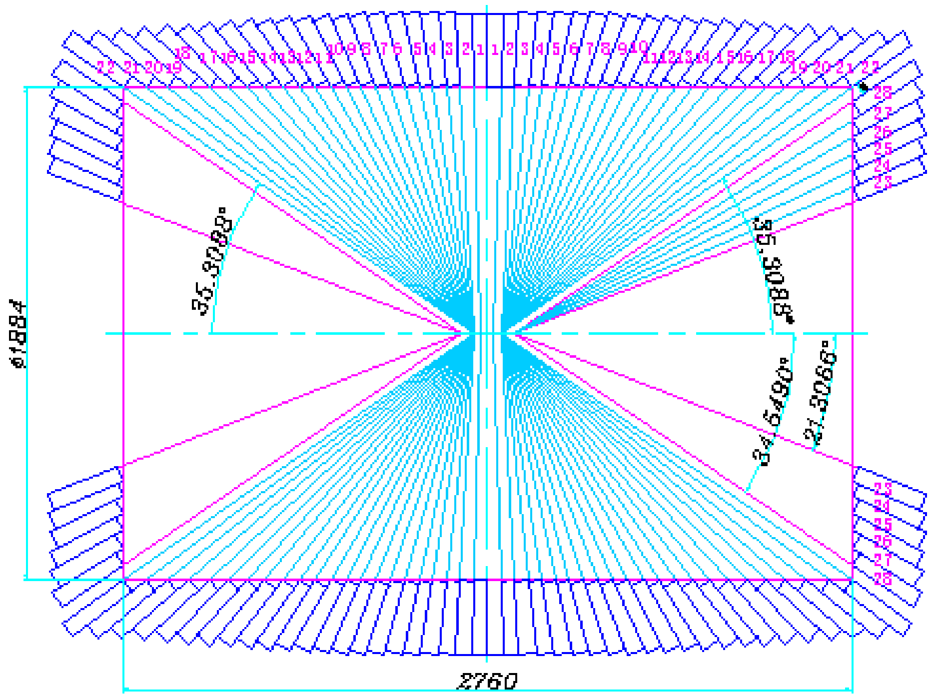
重建
- 高效的簇团寻找和劈裂算法
- 高效的簇射能量和位置重建算法

刻度
- 击中级：准确的电子学读出与真实粒子能量之间的关系
- 簇射级：基于物理事例的能量修正

BESIII量能器软件

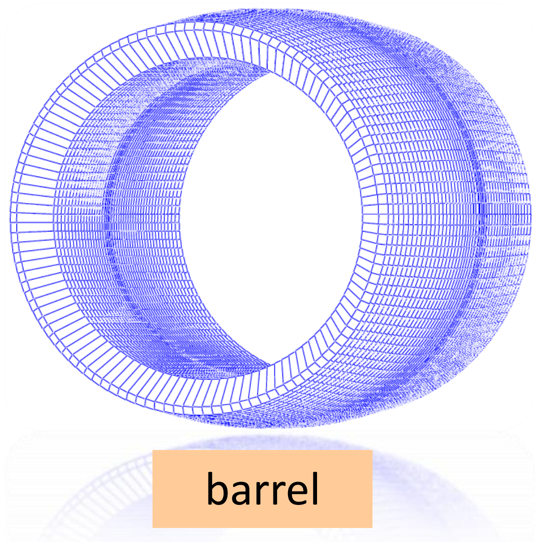
BESIII电磁量能器

- **Based on CsI(Tl) crystal**
  - Crystal sizes :
    - Length 28cm (15.1X_0),
    - typical front and rear sizes 5.2×5.2-6.4×6.4 cm^2
  - Barrel:
    - 120×44=5280 crystals
    - a small tilt of 1.5° in ϕ-directions and 1.5° to 3° in θ-directions
  - Endcaps:
    - 2×(96,96,80,80,64,64) =960 crystals
- **Used to measure energy and position for electrons and photons**
- **Designed performance**
  - Energy range：20MeV - 2GeV
  - Energy resolution: 2.5% @1GeV/c
  - Position resolution: 0.6 cm @ 1GeV/c
  - Provide neutral energy trigger
  - Good e/π identification above 200MeV/c
  - Equivalent electronics noise for each channel is less than 200KeV

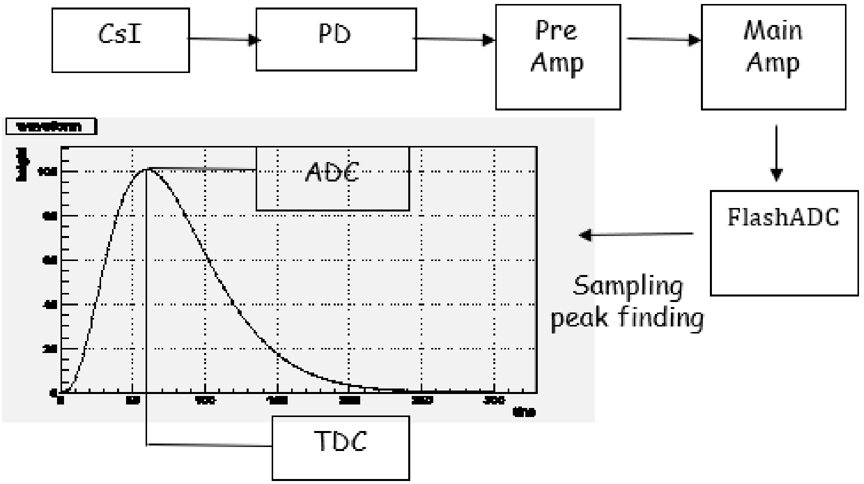


模拟和数字化

- **Geometry description**
  - CsI crystal, casing, PD, front-end electronics, cable, water pipe, and support system
- **Digitization**
  - Waveform generation w/ amplifier response
  - Feature extraction: extract ADC/TDC from waveform

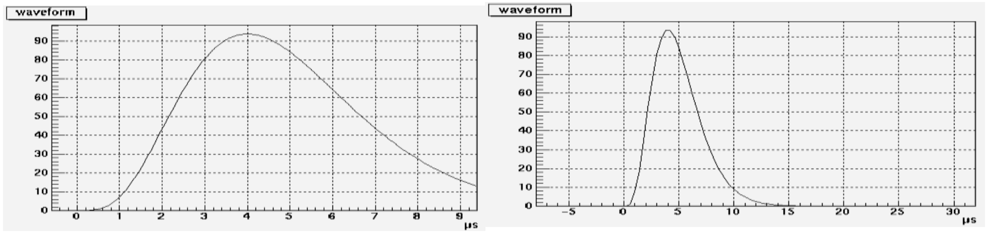


barrel

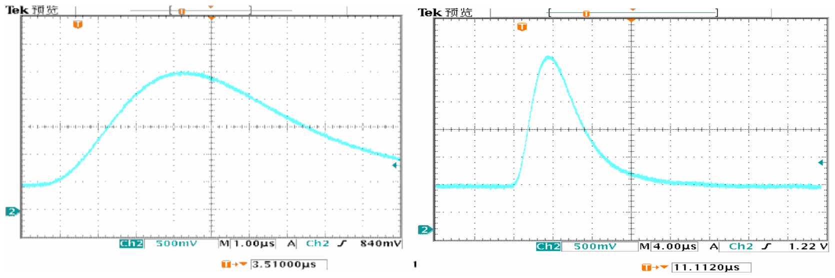


Readout electronics

Simulation



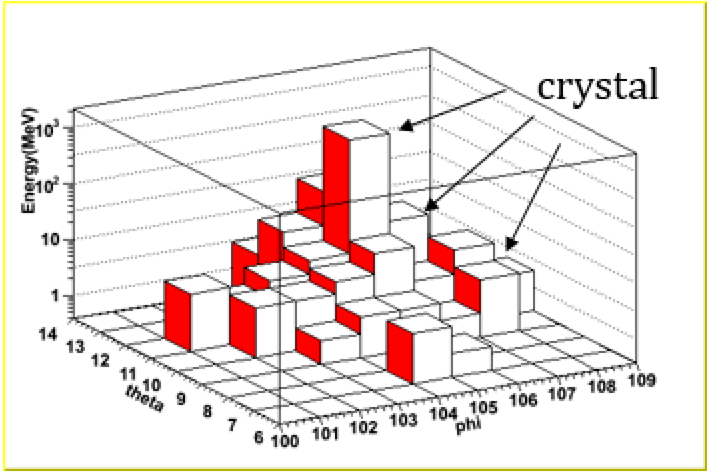
Beam test



Waveform from main amplifier

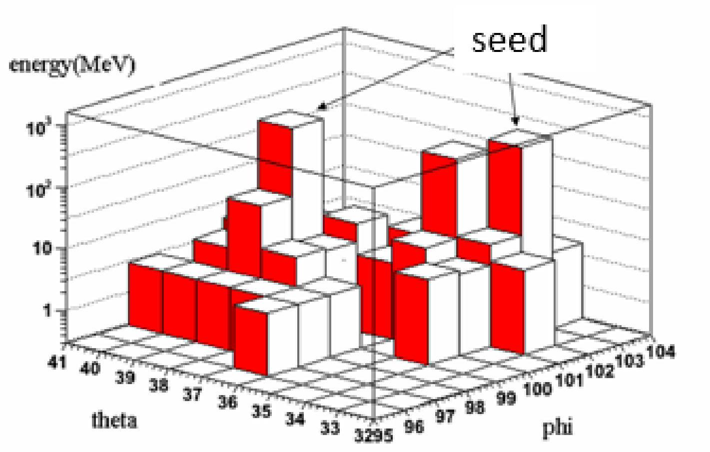
重建

- **Clustering**
  - A contiguous area of crystals with energy deposition that is larg than a threshold
  - Local maximum as the seed of shower



Typical cluster for 1GeV photon

- **Cluster splitting**
  - Need to split if there are more than one seed in a cluster
  - Calculate weight from the i-th shower to a crystal
    - $w_i = \frac{E_{i,exp}}{\Sigma_j E_{j,exp}}$
    - where $E_{i,exp} = E_{i,seed} \times (a_1 \exp\left(-\frac{b_1|x_i - x_c|}{R_M}\right) + a_2 \exp(-\frac{b_2|x_i - x_c|}{R_M}))$
  - Update the E_{shower} and X_{shower}
  - Perform the algorithm recursively

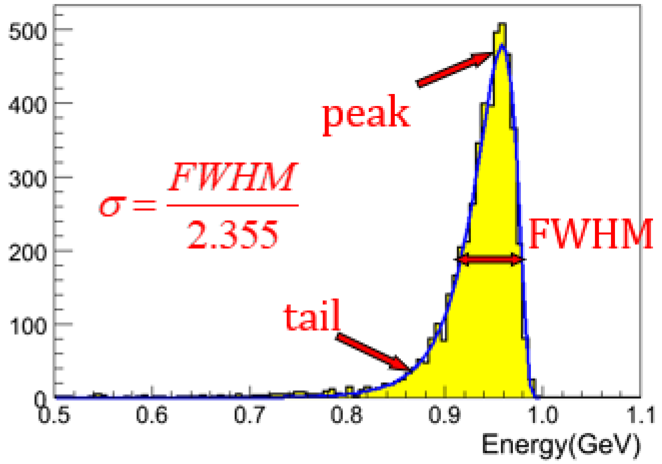


Typical cluster for 1.5GeV π^0

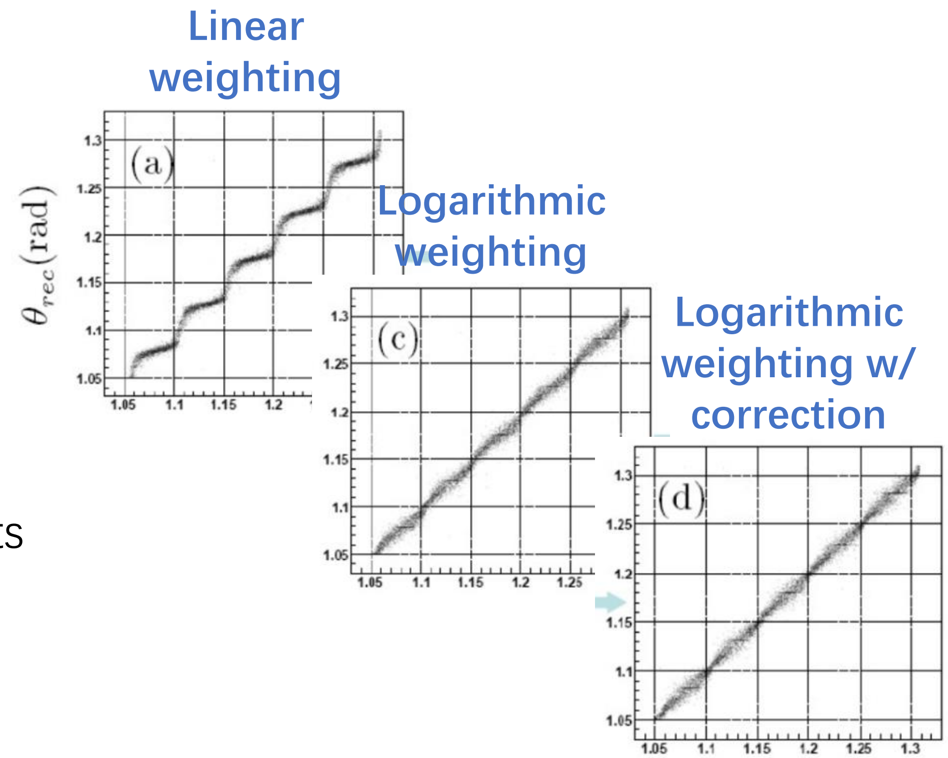
* BABAR Collaboration, B. Aubert *et al.*, Nucl. Instr. and Methods A **479**, 1 (2002)

簇射的能量和位置

- **Shower energy**
  - E3x3, E5x5, Eall: Sum over crystal energies around the seed
- **Shower position**
  - Center-of-gravity method
    - $x_c = \frac{\Sigma_j w_j x_j}{\Sigma_j w_j}$
  - Logarithmic weighting function
    - $w_j = Max(0, a_0 + \ln(E_j) - \ln(E_{tot}))$
  - Position correction
    - Correct bias of reconstructed position by Bhabha events



E5×5 for 1GeV photon



刻度

Crystals Pulse Amplitudes in a clustering algorithm → *Calibration* → **Particle's Energy**

$$E_{e,\gamma} = G \times \mathcal{F} \times \sum_{i}^{\text{Shower}} c_i \times A_i,$$

Absolution energy scale ($G \times \mathcal{F}$)

amplitudes (A_i)

F: Shower energy corrections from single-γ MC

G: Shower energy corrections from π^0 data

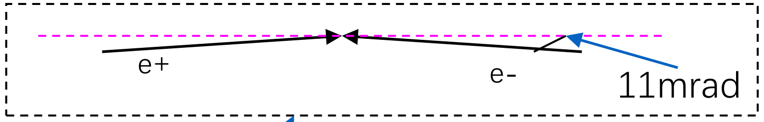
c_i: Crystal energy calibration from Bhabha

G, F, c factors should/must be determined by the Calibration procedure, aiming for the most accurate energy measurement for electrons & photons.

- Detection unit uniformity
- Pre-shower and leakage
- Light yield non-uniformity
- …

单晶体能量刻度

- Use Bhabha events to calibrate the crystal-level constants c_i
- Perform χ^2-fit:



$$\chi^2 = \sum_{k=1}^{N} \left(\frac{E_{exp}^k - \Sigma_i c_i E_i^k}{\sigma(\theta,\phi)} \right)^2$$

where $\boldsymbol{E_{\exp}^k = E_e(\theta,\phi)\, f\,(E_e,\theta,\phi)}$

$E_e(\theta,\phi)$: electron or positron energy from kinematic
$f\ (E_e,\theta,\phi\ )$: the fraction of energy deposited in EMC
E^k_{exp} : expected energy , $\sigma(\theta,\phi)$: energy resolution
i — crystal index k – shower index g_i – calibration constant

簇射能量刻度

- **Step 1: Shower energy correction using simulated single γ events**
  - $E_{5\times5} = E_{5\times5}/F$
- **Step 2: Shower energy correction using π^0 samples**
  - $E_{5\times5} = E_{5\times5}/G$
  - Perform χ^2 fit

Thus in the i–th E_{low} and in the j–th E_{high}, the corrected π^0 mass can be expressed as:

$$m_{\gamma\gamma}^{cor} = \sqrt{2E_{low}\exp(-\alpha_i)E_{high}\exp(-\alpha_j)(1-\cos\theta_{\gamma\gamma})}$$
$$= \sqrt{2E_{low}E_{high}(1-\cos\theta_{\gamma\gamma})}\cdot\exp(-\alpha_i/2-\alpha_j/2)$$
$$= m_{\gamma\gamma}^{raw}\cdot\exp(-\alpha_i/2-\alpha_j/2),$$

$m_{\gamma\gamma}^{raw}$ is the invariant mass of the photon pair calculated with shower energy corrected using MC correction function

The shift (logarithmical) of π^0 mass to MC expected value in the i–th and j–th bin :

$C_{ij} = \alpha_i/2+\alpha_j/2\pm\sigma_{ij}$ σ_{ij} is its statistical error

Define a χ^2 function:

$$\chi^2 = \sum_i\sum_j \frac{(\alpha_i/2+\alpha_j/2-C_{ij})^2}{\sigma_{ij}^2}.$$

Minimizing it yields:

$$\sum_i\sum_j \frac{\alpha_i/2+\alpha_j/2-C_{ij}}{\sigma_{ij}^2}(\delta_{ik}+\delta_{jk}) = 0,$$

$$\delta_{jk} = \begin{cases}1, & \text{if } j=k\\ 0, & \text{if } j\neq k.\end{cases}$$ $k = 1,2,\ldots,n$, here n=13

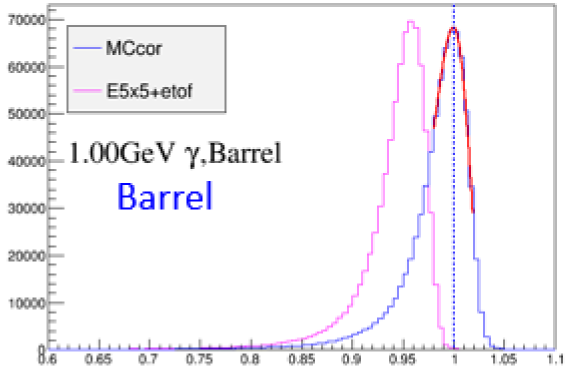
In matrix form $\sum_{m=1}^{n} A_{mk}\alpha_m = B_k,$ $\alpha_k = \sum_{i=1}^{n} A_{ki}^{-1}B_i,$

$$A_{mk} = \sum_i\sum_j \frac{(\delta_{im}+\delta_{jm})(\delta_{ik}+\delta_{jk})}{2\sigma_{ij}^2}, \qquad \Delta\alpha_k = \sqrt{2A_{kk}^{-1}}.$$

$$B_k = \sum_i\sum_j \frac{(\delta_{ik}+\delta_{jk})C_{ij}}{\sigma_{ij}^2}.$$

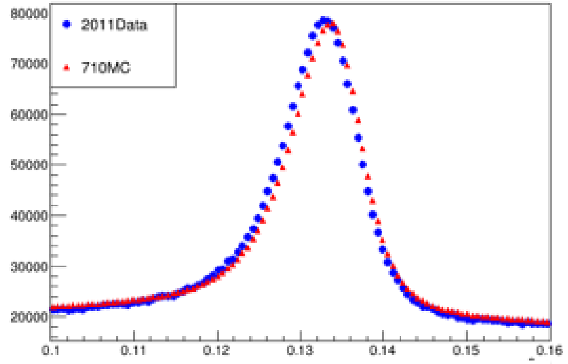
$$C_{ij} = \ln m_{\gamma\gamma}^{data} - \ln m_{\gamma\gamma}^{exp},$$

$$\sigma_{ij}^2(C_{ij}) = \sigma_{ij}^2(\ln m_{\gamma\gamma}^{data}) + \sigma_{ij}^2(\ln m_{\gamma\gamma}^{exp}).$$

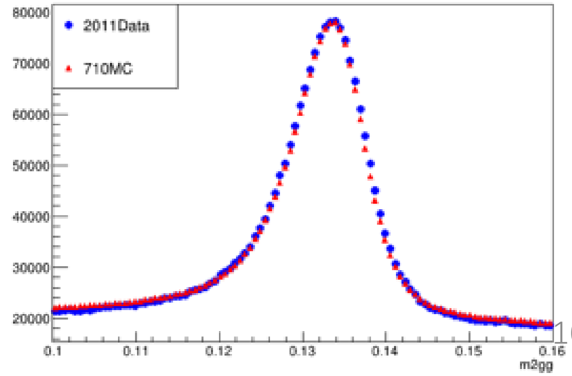


Inclusive π^0 from $\psi'' \to \pi^+\pi^-K^+K^-$+X

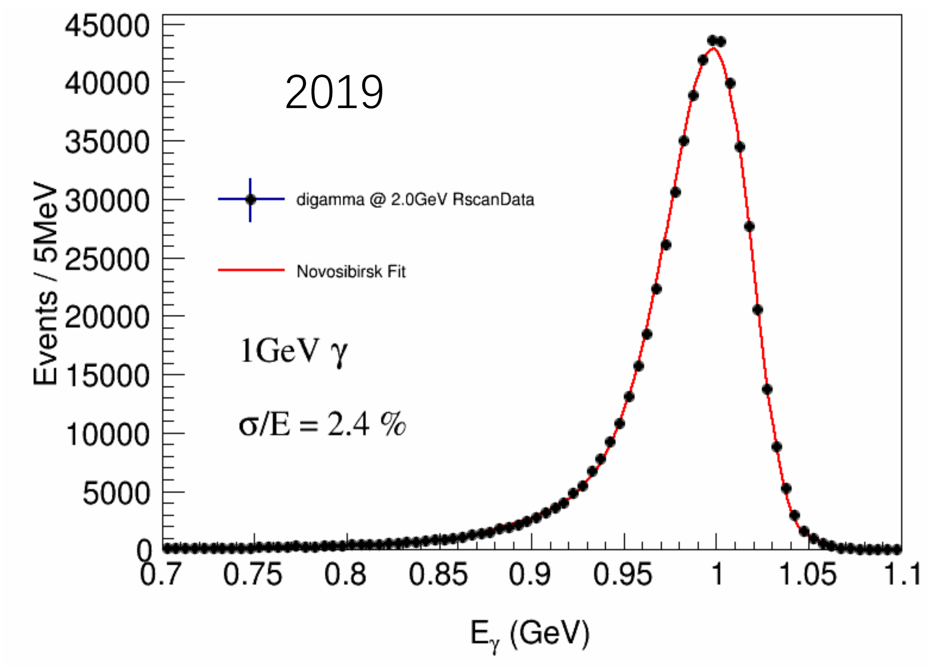
Before π^0calibration for data

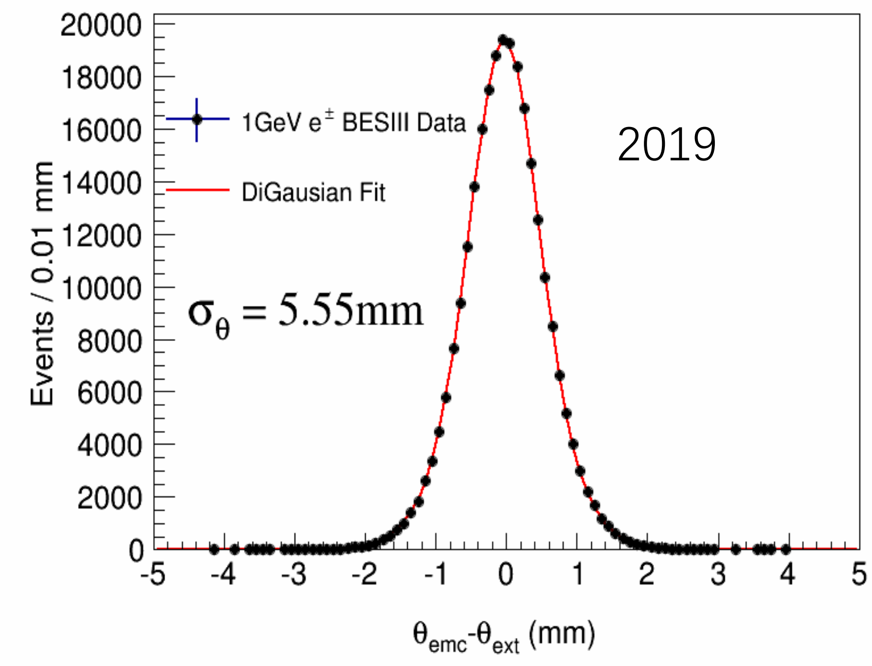


After π^0calibration for data



1 GeV光子的能量和位置分辨





Design objective:

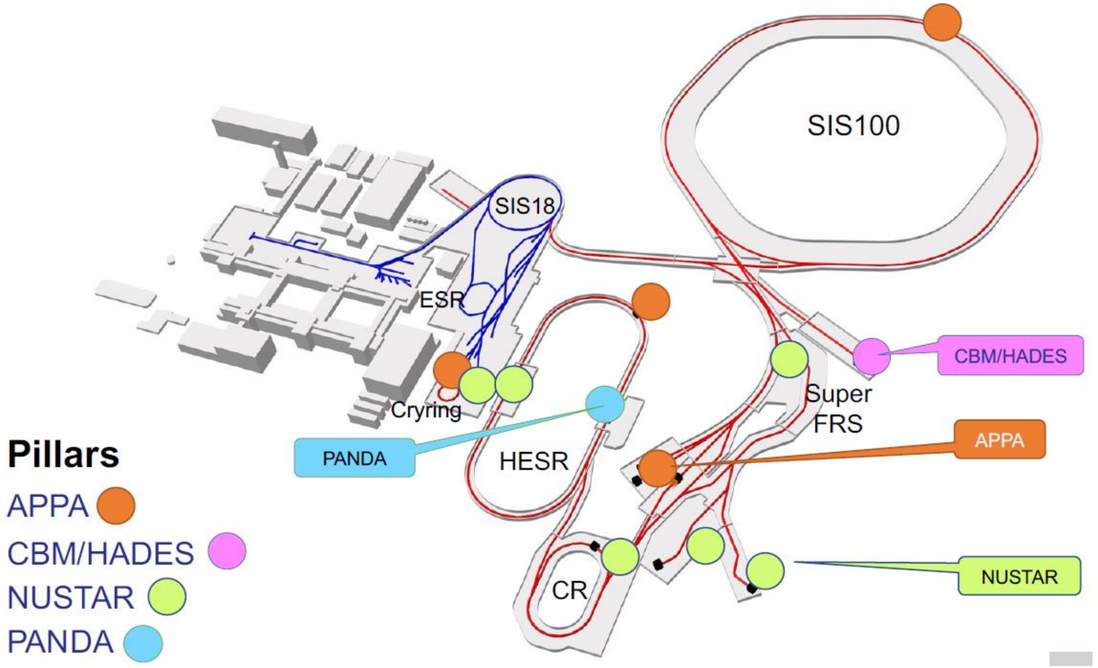
Energy resolution: $2.3\%/\sqrt{E(\mathrm{GeV})} \oplus 1\%$ (2.5%@1GeV)

Position resolution: $\sigma_{X,Y} \le 6mm/\sqrt{E(\mathrm{GeV})}$

PANDA量能器软件

PANDA实验

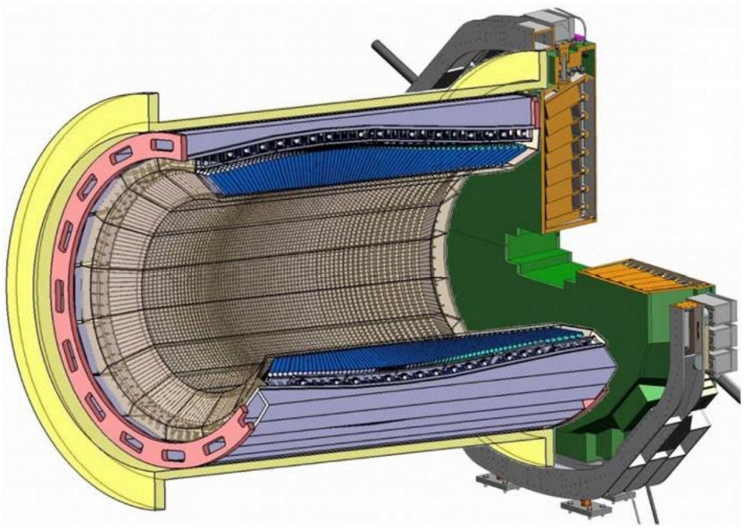
- PANDA: Anti-Proton Annihilations at Darmstadt
- Anti-proton beam between 1.5 GeV/c to 15 GeV/c shoots on fixed target
- $\sqrt{s}$: 2.3 GeV ~ 5.5 GeV
- Luminosity: 2×10^{32} cm^{-2} s^{-1}
- Complementary physics programs to BESIII
  - $p\bar{p}$ can produce particles with any quantum number



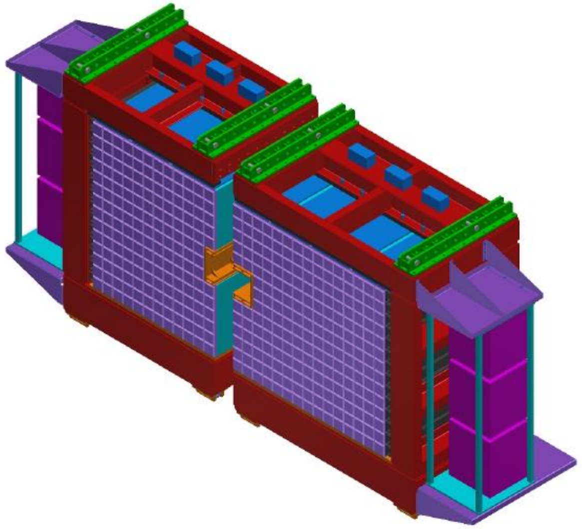
PANDA电磁量能器

- **Target Spectrometer:**
  - Barrel and two endcaps
  - 16,000 crystals, improved PbWO4
  - X_0 = 0.89 cm, R_M = 2.00 cm, x4 light yield at -25°C
  - For barrel EMC, 11360 crystals, the average lateral size of crystal is 21.3mm
- **Forward Spectrometer:**
  - Shashlik type sampling calorimeter
- **Designed energy and spatial resolution for photons**
  - $\leq 1\% \oplus \frac{\leq 2\%}{\sqrt{E/GeV}}$
  - $\leq 0.5°$(backward), $\leq 0.3°$(barrel), $\leq 0.1°$(forward)

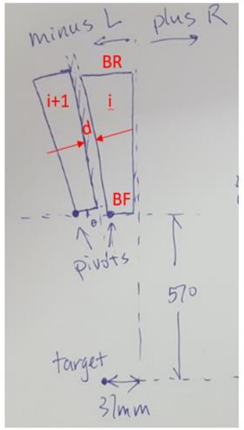
Target Spectrometer

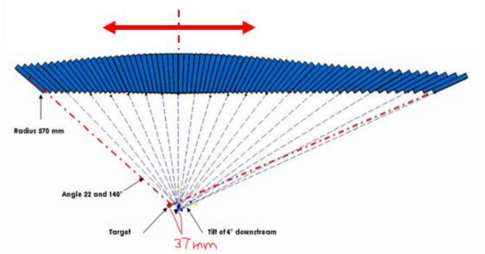


Forward Spectrometer

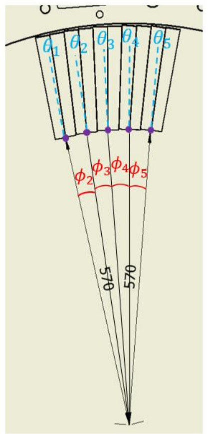


桶部几何的构建

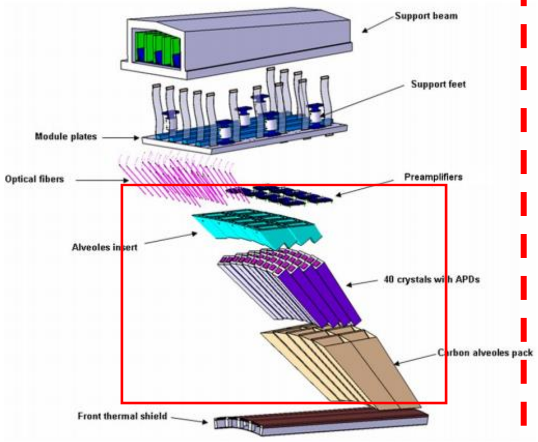


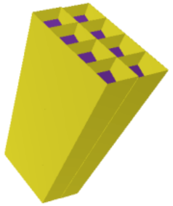


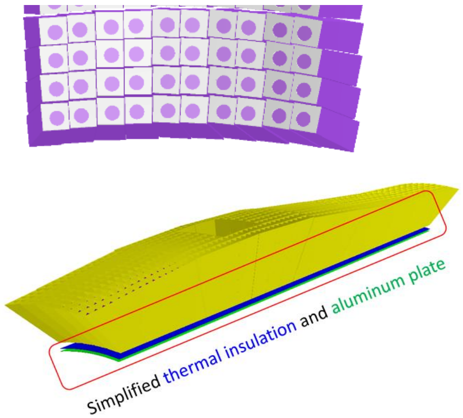
- z positions of the crystals are defined by the gap d and the crystal dimension
- For the (i+1)th crystal (minus)
  - $z_{i+1} = z_i - (BF + d)/cos\theta_i$
  - where $\theta_{i+1} = \theta_i + \text{atan}(\frac{BR_i - BF_i}{L})$
- Place the crystals from center to side one by one

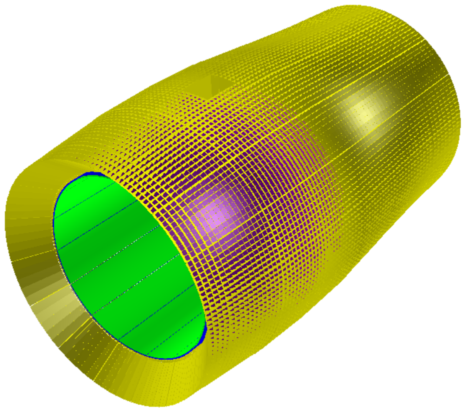


✓ 根据最新硬件设计，详细构建了桶部量能器的晶体和非灵敏物质。



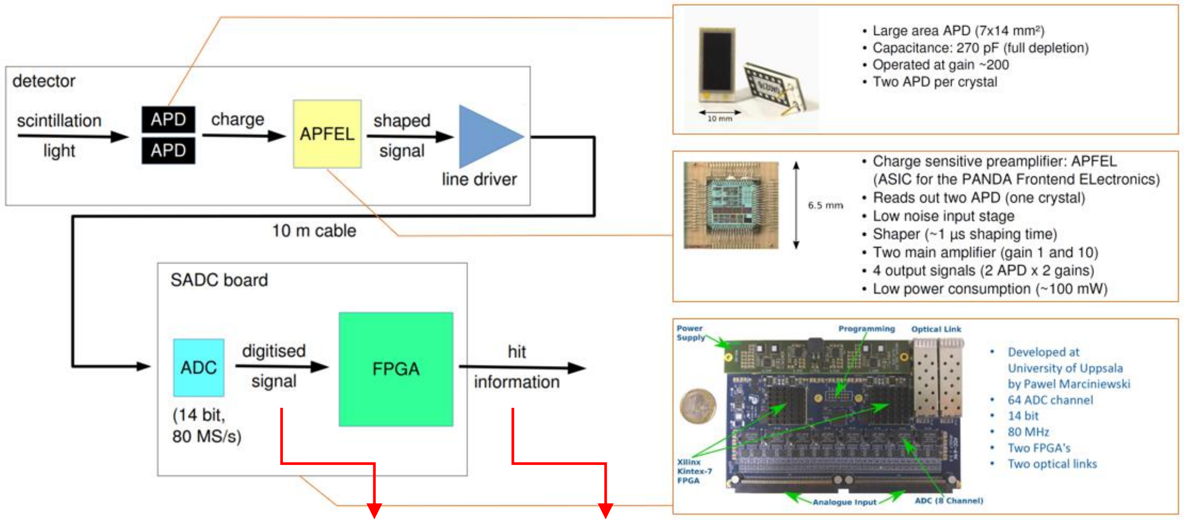






数字化 (I)

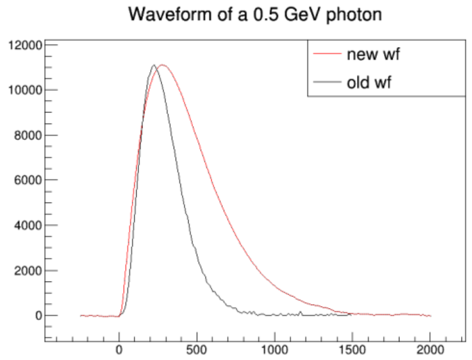
与Mainz合作完成后端盖数字化



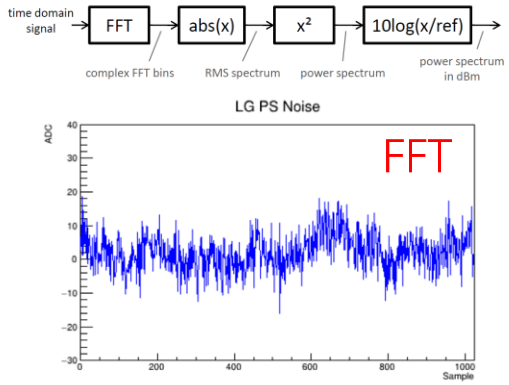
Duo APD readout
Two-gain amplifier
readout*4

64 ADC channel
FPGA*2

数字化：信号产生 + 特征提取



波形



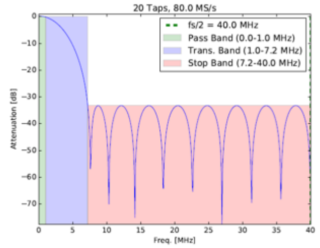
噪声

信号产生：
- 真实波型的产生
- 噪声的模拟
  - 基于FFT频谱分析
  - 重点优化了软件速度（复杂度O(n) -> O(1)）
- 实现了4个读出的模拟

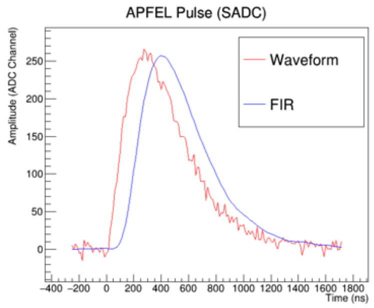
数字化 (II)

<u>特征提取：</u>
- 低通滤波器对波形进行光滑
- 通过FPGA算法
  - 提取波形的时间和幅度
  - 以及分离交叠信号

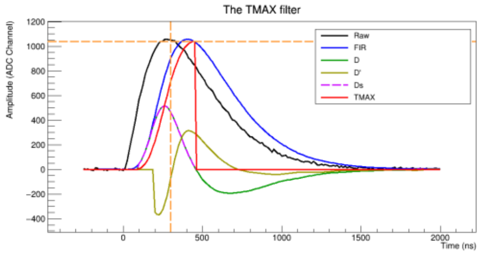
光滑



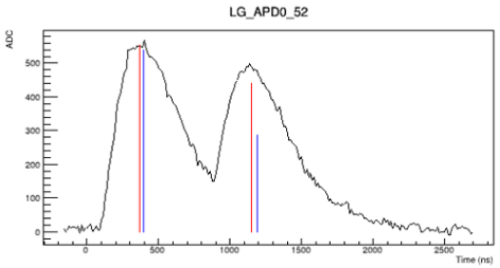
Low pass filter to smooth the waveform
(20 coefficients, ~10 cycle clocks latency)



时间/幅度提取



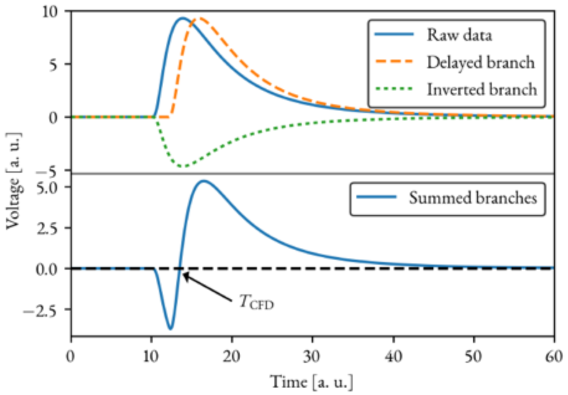
分离交叠信号



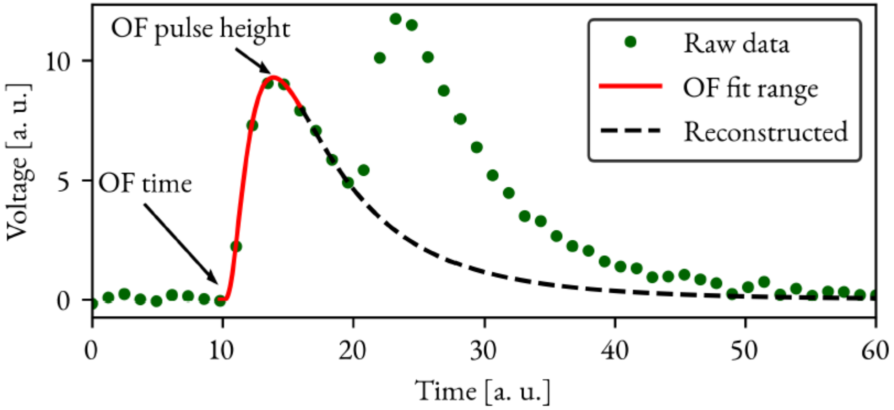
Feature Extraction (特征提取)

与Stockholm U合作完成前向数字化

恒比定时: 确定起始时间



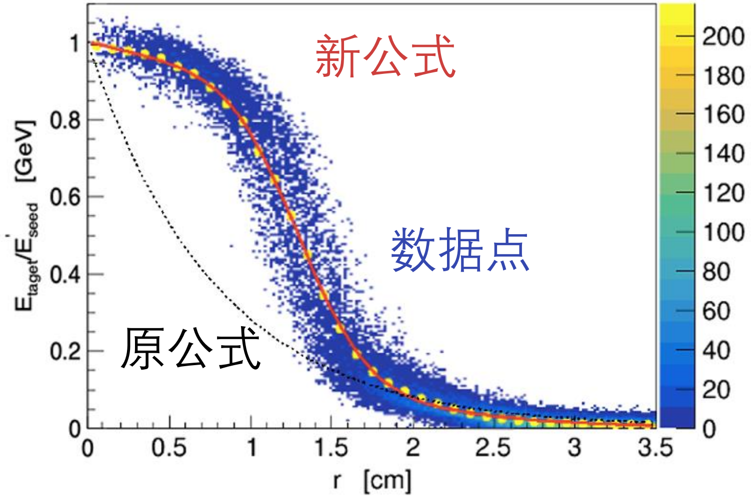
最优滤波: 精确提取时间和幅度，处理堆积信号

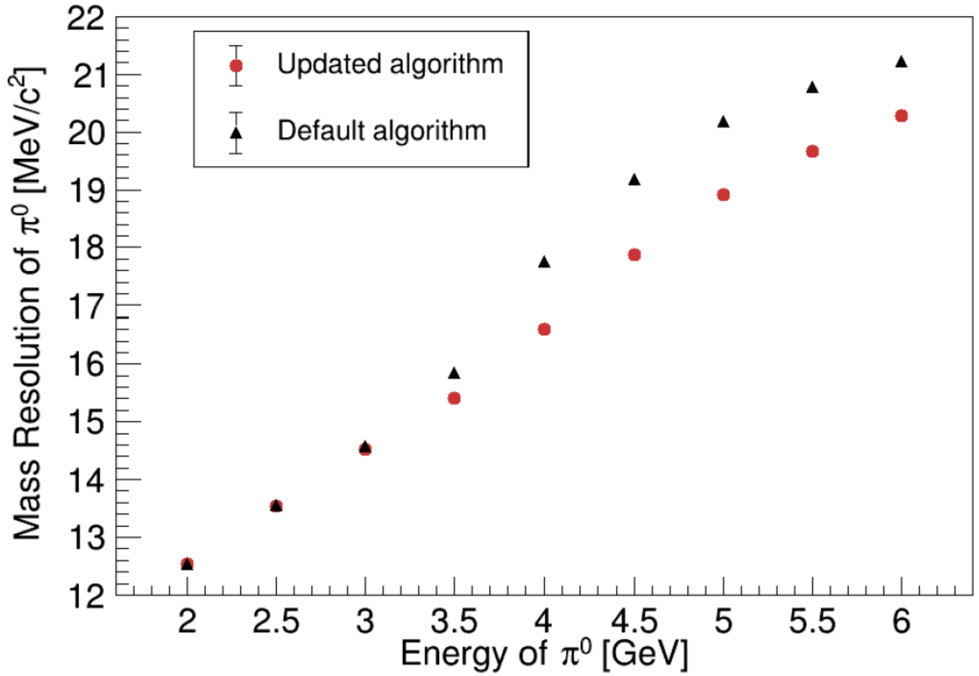


簇团劈裂算法的改进

考虑了**探测器的颗粒度**后，改进了簇团劈裂算法中的簇射横向发展公式：

$$E_{target} = E_{seed} \times e^{-2.5r/R_M}$$

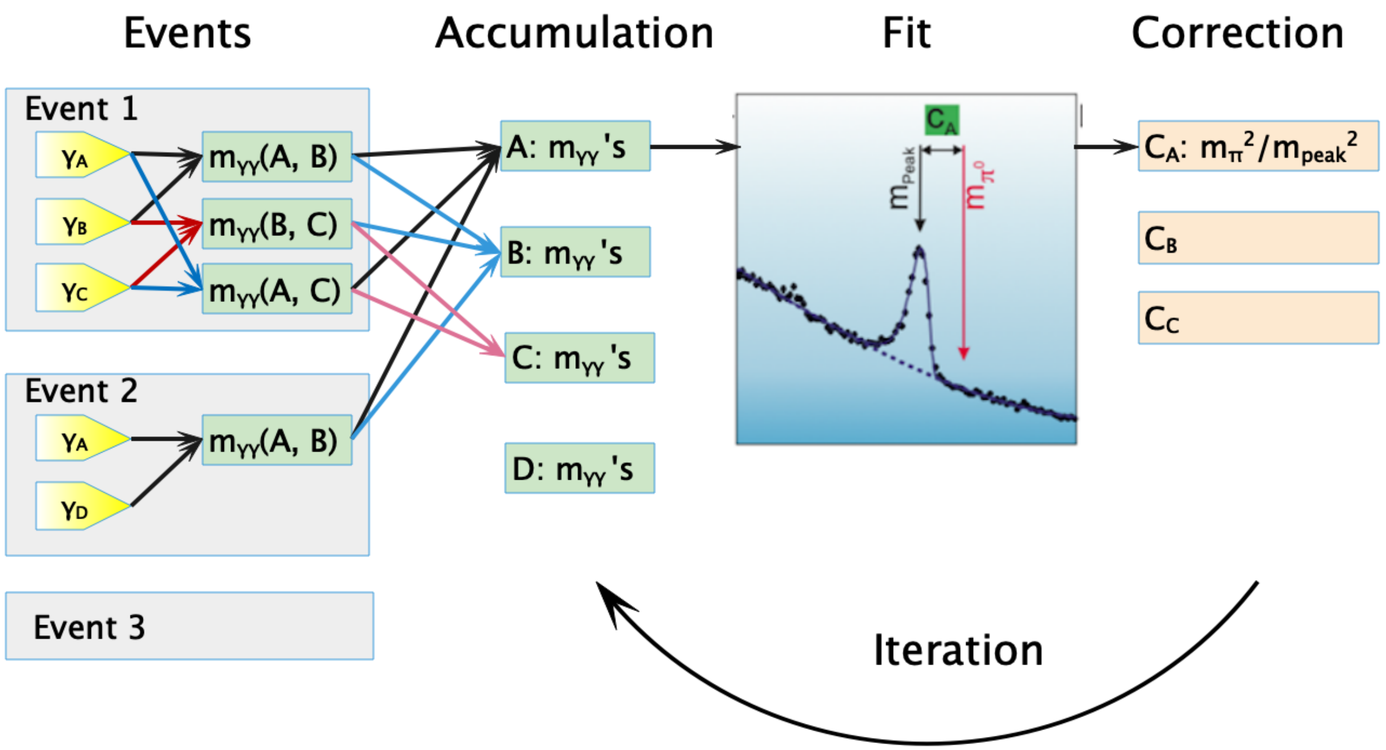




提高了高动量π^0的质量分辨

刻度 (I)

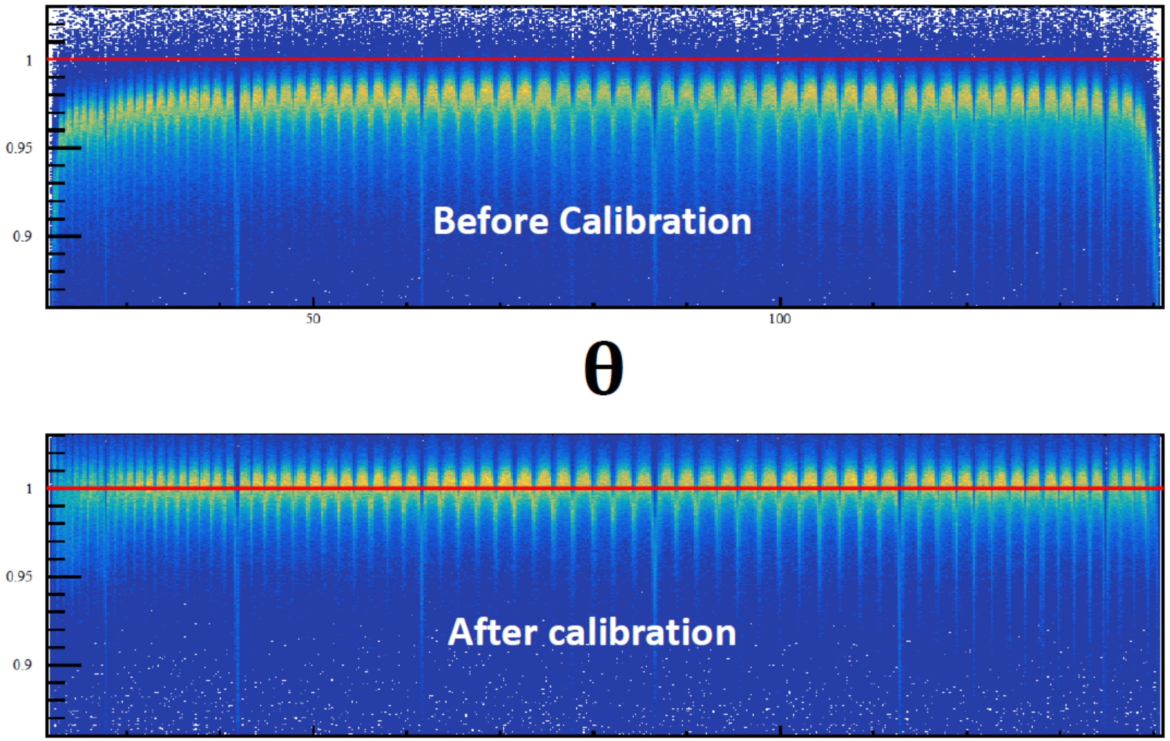
Calibration algorithm



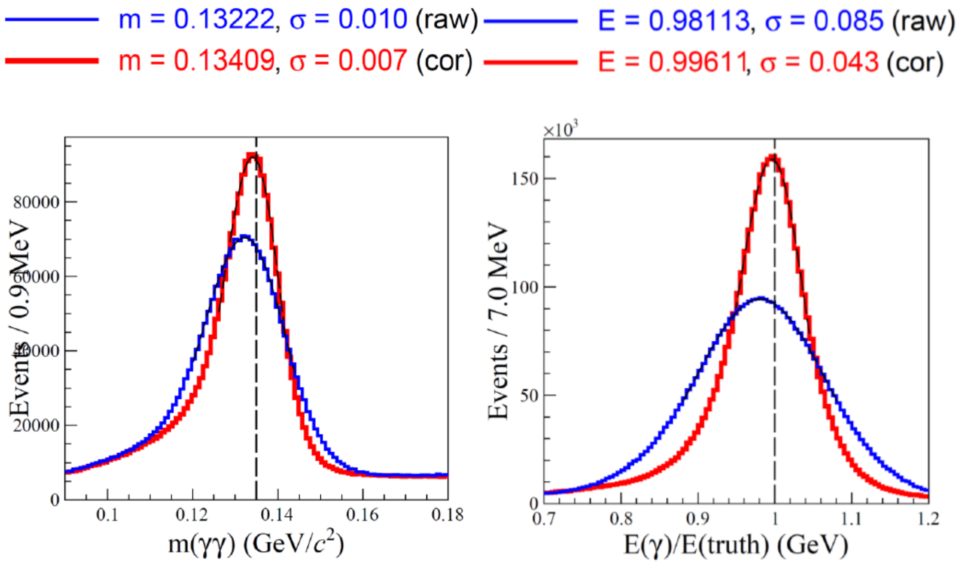
- **No Bhabha events for calibration**
- **Develop the algorithm using π^0 events**
  - Single π^0 events
  - $p\bar{p} \rightarrow \pi^0\pi^0\ \pi^0$ events

刻度 (II)

Test with single γ events



Test with $p\bar{p} \rightarrow \pi^0\pi^0\pi^0$ events



* An correction of energy leakage is included in the calibration

总结

- **开发了完整的BESIII量能器离线软件，探测器性能优于设计指标：**
  - 能量分辨：2.4% @ 1 GeV γ (桶部)
  - 位置分辨：5.55 mm @ 1GeV e^- (桶部)

- **对PANDA量能器进行了多项重要的软件改进，包括：**
  - 重新构建了桶部几何
  - 基于最新电子学设计的数字化算法的开发
  - 簇团劈裂算法的改进
  - 刻度框架和算法的开发

谢谢！

备用

PANDA Schedule

Current Status

- Construction of many Phase 1 systems has started
- Integration and infrastructure planning progressing
- Delays in several parts due to delayed funding or contracting
- Covid-19 needs to be accounted still

Installation periods according to present plans

- Installation period 1: solenoid, dipole, supports etc. in parallel with installation of technical building infrastructure
- Installation period 2: all other systems after building completed.

Boundary conditions for plan revision

- Completion of PANDA hall 2 years later than initially planned
- Start of installation period 1 on June 6 2024
- Mitigation: testing and pre-assembly of parts at other sites, storage

Ready for beam end 2026